Radiation Hardness of VCSEL/PIN

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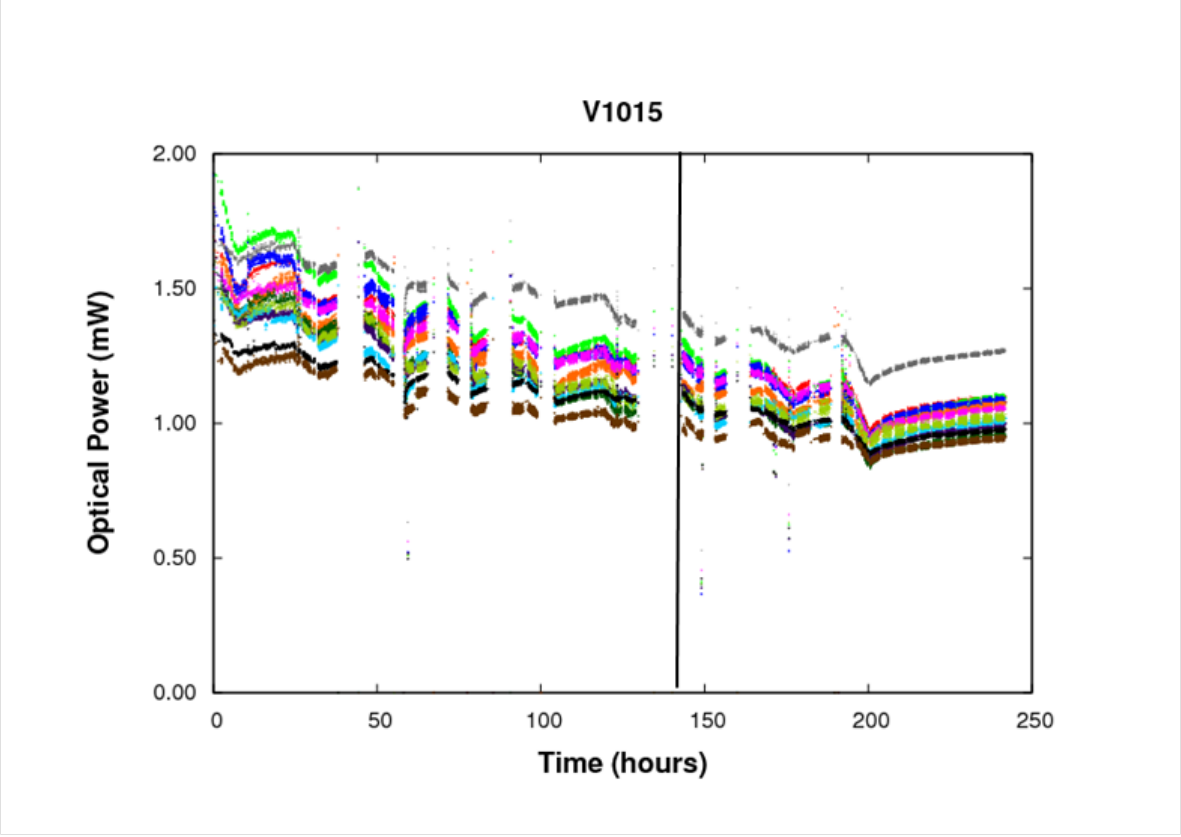
Introduction

- Irradiated VCSEL/PIN diodes with both 24 GeV p and 300 MeV π beams
- Studied effect of proton irradiation on:
  - VCSEL optical power
  - VCSEL threshold current
  - PIN responsivity
- Compared effect of pion irradiation on:
  - VCSEL optical power
  - PIN responsivity
- Found some evidence of radiation damage affecting PIN leakage current

Irradiation

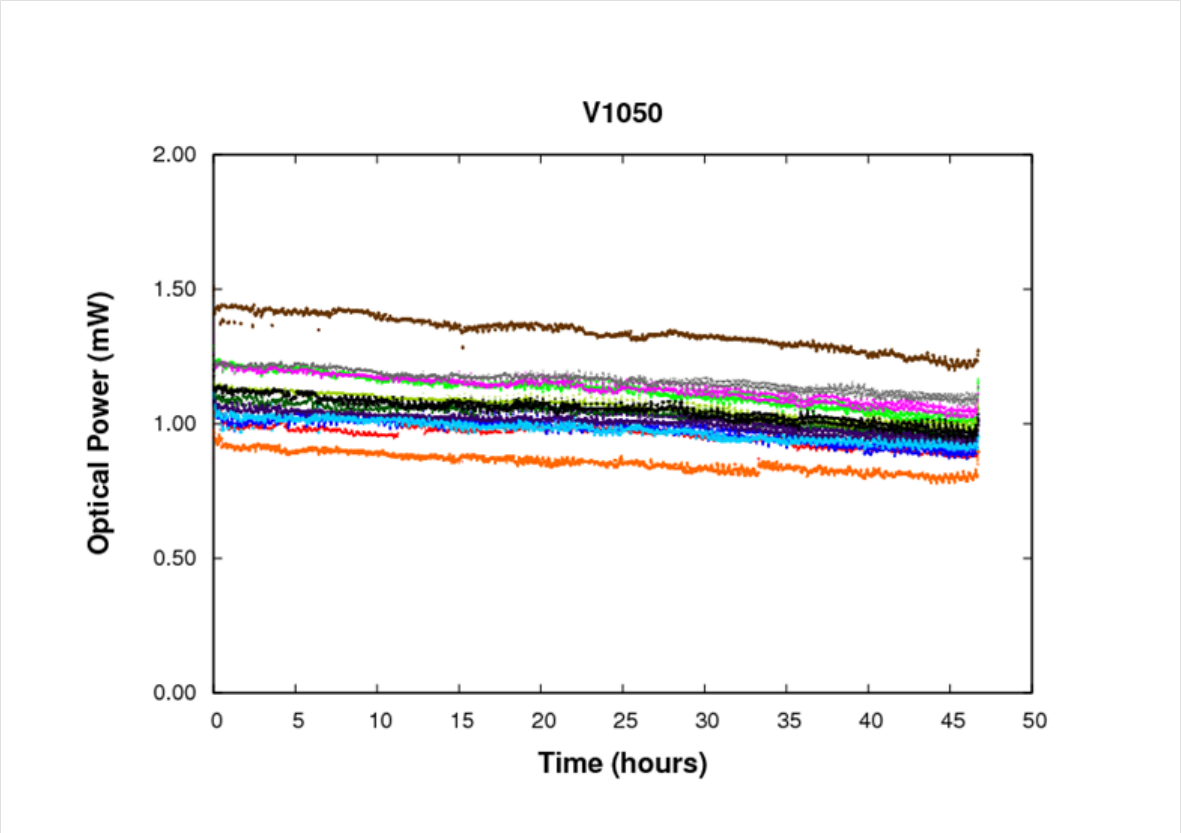
- Compared the effects of the two types of beams to test the Non-Ionizing Energy Loss (NIEL) hypothesis
- NIEL hypothesis posits that radiation damage to a material caused by a particle is proportional to the energy lost by the particle through Coulomb interaction with nucleons in the material
- Protons undergo more non-ionizing energy loss than pions, so NIEL hypothesis predicts more damage from the proton beam
- Without the effect of NIEL, a 300 MeV π is 1.5$\times$ more damaging than a 24 GeV p
- Therefore, supplied total doses of 4.3 (4.1) $\times 10^{14}$ π/cm^2 and 6.4 (6.0) $\times 10^{14}$ p/cm^2 to separate samples of PIN (VCSEL) to compare the degradation

VCSEL: Optical Power (p Irradiation)



- Plot shows optical power versus time, vertical line indicates equivalent dose to that from pion irradiation
- VCSELs were alternated between irradiation and annealing
- Visible on plot as decrease and increase of optical power

VCSEL: Optical Power (π Irradiation)

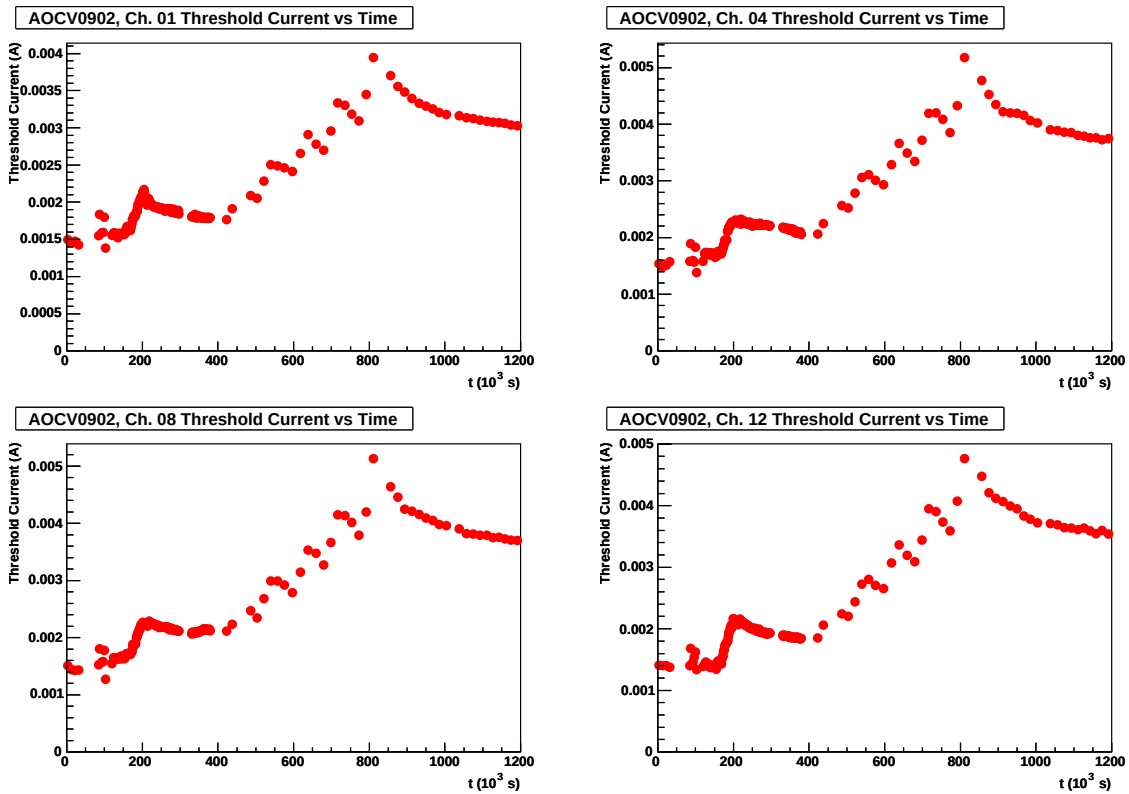


- Same plot as previous slide for VCSELs irradiated with pion beam

VCSEL: Optical Power Comparison

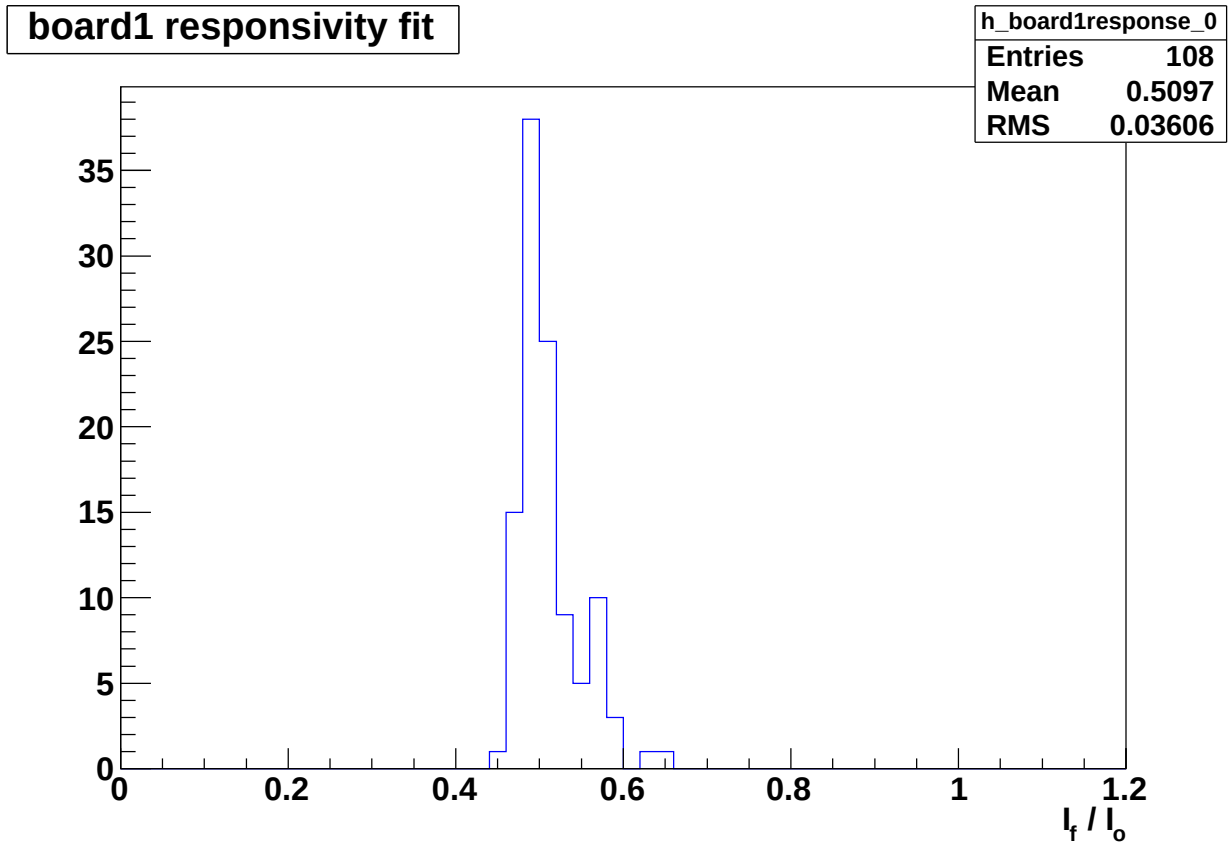
- No beam-off annealing period in pion irradiation
- Overall level of degradation difficult to compare due to annealing
- Must repeat the proton beam irradiation without beam-off annealing periods for better comparison

VCSEL: Threshold current (p Irradiation)



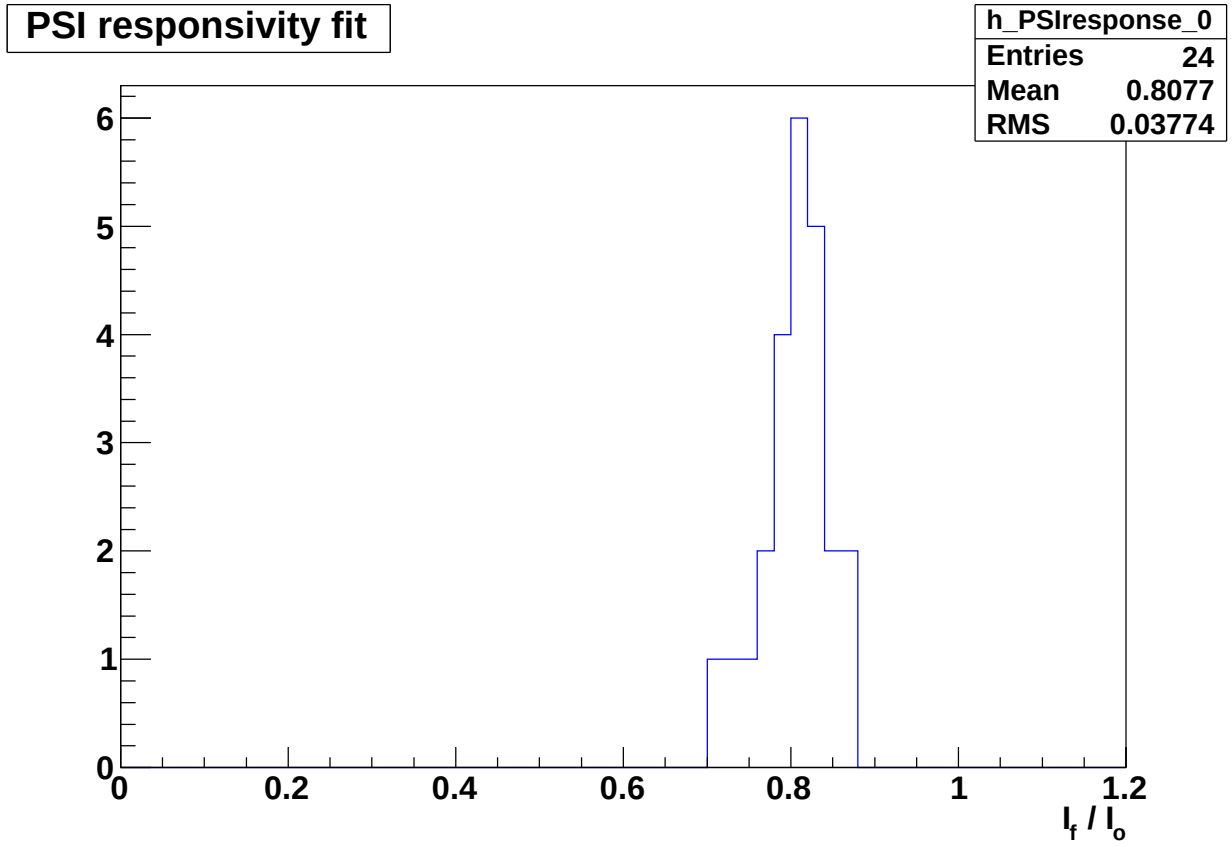
- Threshold current increases under irradiation and partially recovers under annealing
- Periods of irradiation and annealing visible on plot as periods of increasing and decreasing threshold current

PIN: Responsivity (p Irradiation)



- Responsivity (ratio of induced current to incident optical power) decreases under irradiation
- Fit responsivity (as current at 1 mW) vs time to determine the initial and final responsivities
- Plot shows the distribution of the ratio of final to initial responsivity

PIN: Responsivity (π Irradiation)

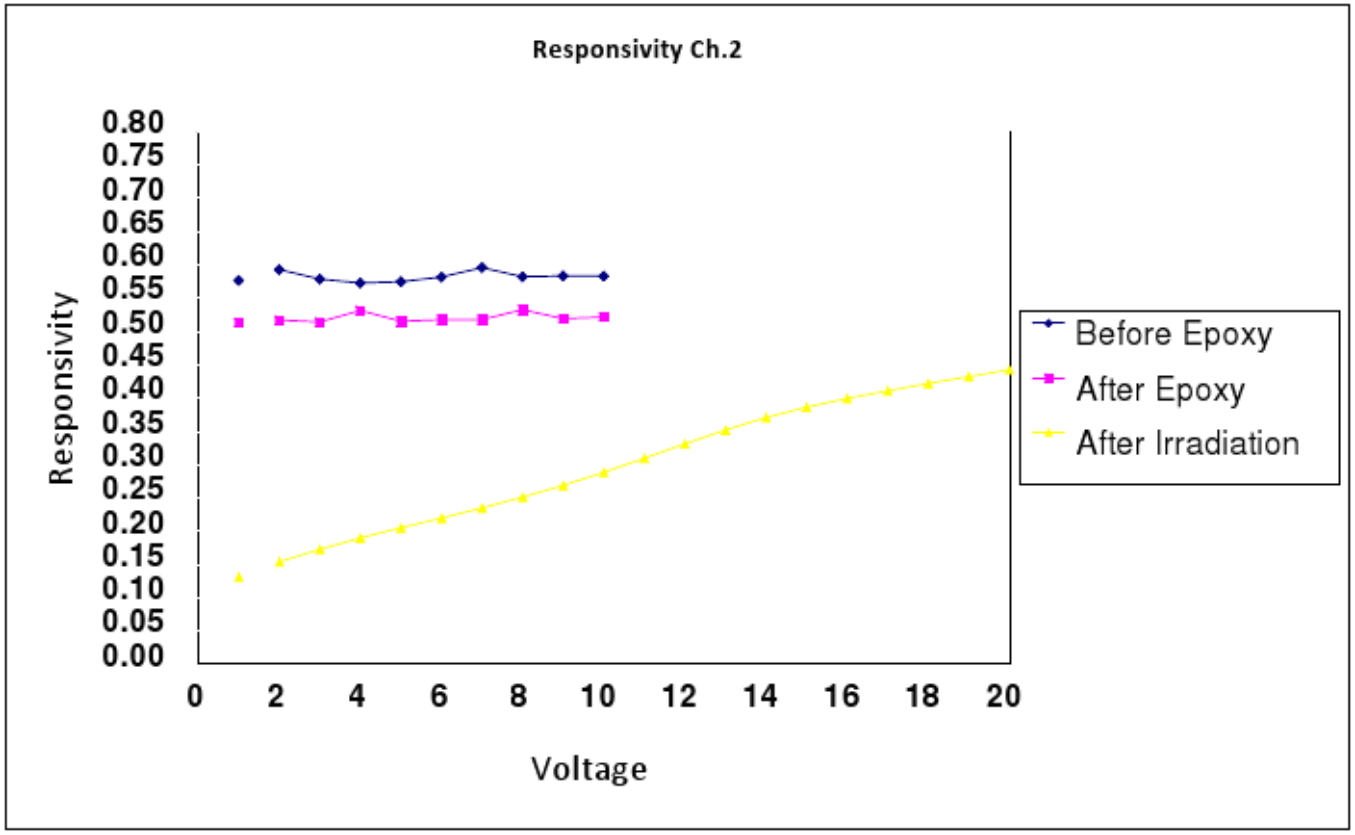


- Same plot as previous slide for PINs irradiated with pion beam

PIN: Responsivity Comparison

- Average loss of responsivity under proton irradiation (6.4×10^{14} p/cm^2): 49%
- Average loss of responsivity under pion irradiation (4.3×10^{14} π/cm^2): 19%
- $\Rightarrow$ Substantially more degradation in responsivity from proton irradiation
- Supports the NIEL hypothesis

PIN: Bias Voltage Effects on Responsivity (p Irradiation)

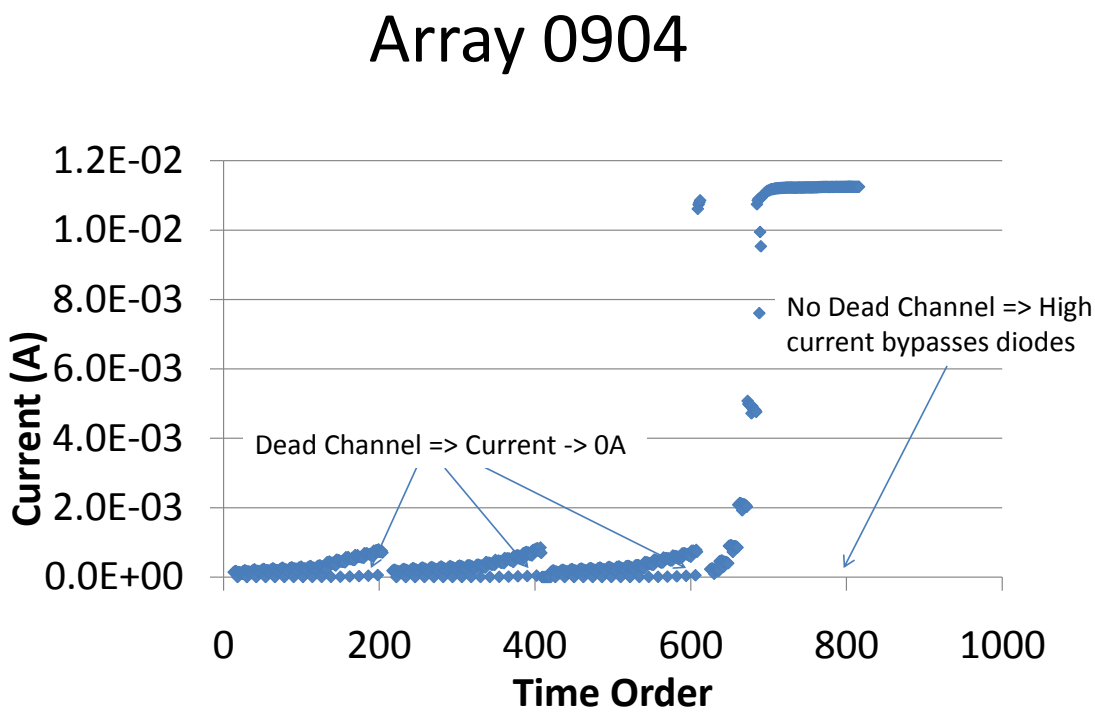


- Before irradiation, responsivity is a plateau for typical values of bias voltage (i.e. < 10 V)
- After irradiation, responsivity is no longer in the plateau, but increases with bias voltage instead
- Higher operating voltage partially recovers responsivity

PIN: Leakage Current (p Irradiation)

- All PINs discussed so far were manufactured by ULM
- Before ULM, tried PINs manufactured by Optowell
- Post irradiation, the PINs were subjected to a stress test:
  - Supplied 1 mW optical power
  - Thermal cycled: 20 C$\rightarrow$-25 C$\rightarrow$10 C$\rightarrow$50 C
  - At each temperature, ramped to the manufacturer specified maximum bias voltage (40 V)
- Discovered that near the top of the ramp at 10 C, $\sim$ 1% of PINs suddenly produce high leakage current
- Leakage current reset by removing the bias voltage, but returns if the bias volage is returned

PIN: Leakage Current (p Irradiation) (ctd.)



- The initial current spike, reset to low leakage, and subsequent current spike are visible in the plot
- Unable to recreate the behavior on non-irradiated PINs, possibly due to small sample size
- However, only Optowell PINs show this behavior

Conclusions

- VCSEL optical power and threshold current degrade when irradiated but partially recover when annealed
- NIEL effect on VCSEL damage is difficult to test due to annealing
- PIN diodes are damaged more by the protons than by pions, in accordance with the NIEL hypothesis
- Only Optowell PINs had problems with post-irradiation leakage current
- Unclear whether this was an effect of radiation damage due to limited statistics